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# A Scattering Center-Based Prediction Method for Shadowing and Two-Body Interactions

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**Abstract:** The electromagnetic interaction between two closely-spaced objects can have a significant impact on the total radar cross section. In this paper, we present a simple approximate method for modeling the two-body interaction by adjusting scattering centers to account for shadowing and diffraction phenomenon. The problem is simplified by replacing the shadowed object with discrete ideal isotropic scatterers corresponding to the object's scattering center model. By applying reciprocity, the Green's function in the presence of the shadowing object is then used to estimate the adjustment to each scattering center due to the shadowing object. The model predictions are compared to rigorous moment method codes as well as to static range RCS measurements to demonstrate the limits of applicability of the current approach.<sup>2</sup>

**Keywords:** Radar Cross Section, Numerical Methods

## 1. Introduction

Scattering center models present an efficient and compact representation of RCS over all viewing angles. However, difficulty is encountered when objects are closely spaced, since the radar return from both objects may be quite different from the simple superposition of the returns from the individual objects. In this method, we consider a target represented by a scattering center model located behind a canonical shadowing object. The requirement for such a canonical object is that the scattered fields (including the near field) are known throughout the entire volume occupied by the scattering center model.

In this paper, we provide a theoretical formulation of the two-body solution method. We show experimental evidence for the validity of the technique by examining the case of two PEC spheres of different sizes. The shadowing of one sphere by the other is examined experimentally by placing the spheres in a static range. The results are compared to those predicted by the current method for both polarizations. We conclude by giving explicit formulas for shadowing by planar PEC objects and comparing two different formulations of the shadowing solution with Method of Moment (MoM) simulation.

## 2. Theoretical Formulation

The primary concept of the scheme is to evaluate the field due to the shadowing object at the location of the scattering center of interest, and use this field to adjust the value of the scattering center. This avoids the much more difficult proposition of a full-wave electromagnetic simulation of both objects. The geometry for the general case is shown in Fig. 1. The coordinate system is defined with respect to the shadowing body, and we typically choose the origin to coincide with the center of the shadowing body. We also denote the vector  $\mathbf{k}$  as the direction of plane wave incidence. We define a vector  $\xi$  in

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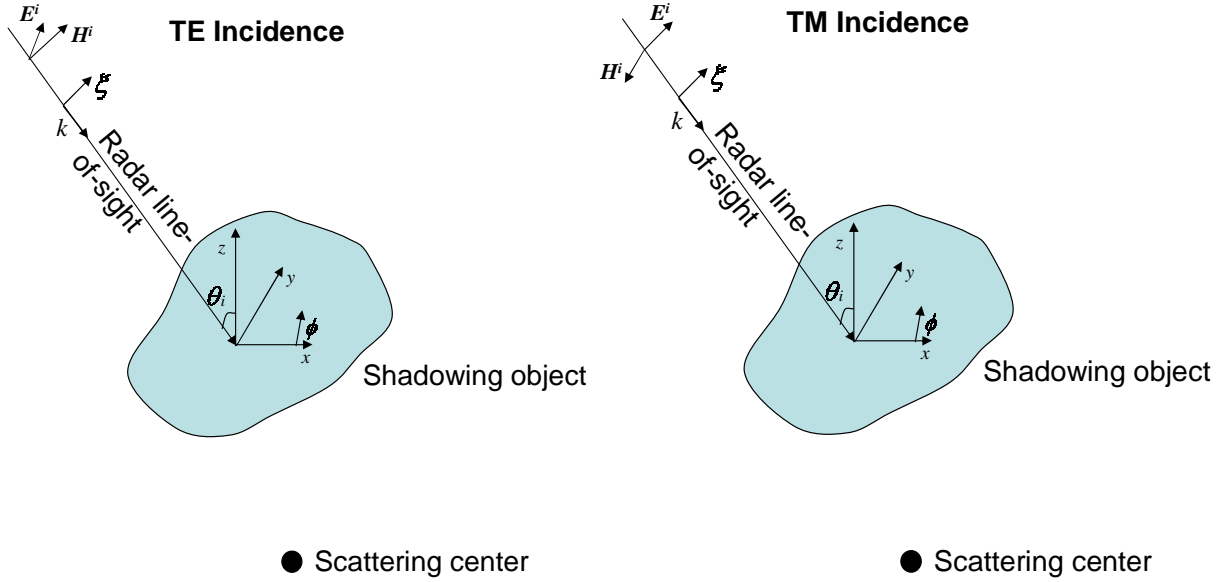


Fig. 1: Two-body geometry and associated coordinate system for both the TE incidence case and the TM incidence case.

the plane of incidence such that

$$\mathbf{y} \times \xi = \mathbf{k}. \quad (1)$$

If the incident plane wave is represented by an impulse current source at infinity, the Green's function can be computed by evaluating the fields at the observation point (the scattering center). If we take the original scattering matrix to be

$$\overline{\sqrt{\sigma}} = \begin{pmatrix} 0 & 0 & 0 \\ 0 & HH & HV \\ 0 & VH & VV \end{pmatrix}, \quad (2)$$

the corrected RCS of the scattering center in the presence of the shadowing body (assuming a source at  $\mathbf{r}_1$  and scatterer at  $\mathbf{r}_2$ ) can be expressed in  $(k, y, \xi)$  coordinates as [1]

$$\overline{\sqrt{\sigma_{new}}} = \bar{\mathbf{G}}(\mathbf{r}_2, \mathbf{r}_1) \cdot \overline{\sqrt{\sigma}} \cdot \bar{\mathbf{G}}(\mathbf{r}_2, \mathbf{r}_1)^T = \begin{pmatrix} 0 & 0 & 0 \\ 0 & g_{yy} & g_{y\xi} \\ 0 & g_{\xi y} & g_{\xi\xi} \end{pmatrix} \cdot \overline{\sqrt{\sigma}} \cdot \begin{pmatrix} 0 & 0 & 0 \\ 0 & g_{yy} & g_{\xi y} \\ 0 & g_{y\xi} & g_{\xi\xi} \end{pmatrix}, \quad (3)$$

where  $g_{ii}$  are the components of a rank-2 tensor  $\bar{\mathbf{G}}$ , which is defined such that

$$\bar{\mathbf{G}} = \bar{\mathbf{G}}_0 \cdot \bar{\mathbf{G}}_{0,\text{FS}}, \quad (4)$$

where  $\bar{\mathbf{G}}_{0,\text{FS}}$  is the free space Green's function and  $\bar{\mathbf{G}}_0$  is the Green's function in the presence of the shadowing body. Note that in (3), the range phase factor is assumed to be included in  $\overline{\sqrt{\sigma}}$ .

There are two possible formulations for defining the dyadic Green's function referenced above. This is because the incident plane wave can be represented by either an impulse electric source at infinity or an impulse magnetic source at infinity.

In the first formulation, which we shall call the M/H formulation, an impulse magnetic current  $\mathbf{M}_1$  is placed at infinity to create the plane wave. The  $y$  and  $\xi$  components of the resulting magnetic field in the presence of the shadowing body are computed at the scattering center location  $\mathbf{H}_1$ . The scattering matrix then relates this field to currents  $\mathbf{M}_2$ , which then re-radiate toward the source, inducing a

magnetic field at the source  $\mathbf{H}_2$  which can be computed using the reciprocity theorem involving only magnetic sources and magnetic fields.

In the second formulation, which we shall refer to as J/E, the incident plane wave is represented by placing an electric current  $\mathbf{J}_1$  at infinity (at right angles to the current  $\mathbf{M}_1$  used to create the same plane wave). The resulting electric field  $\mathbf{E}_1$  is observed at the scattering center location, which then radiates currents  $\mathbf{J}_2$  back toward the source. The reciprocity theorem is used once again with only electric currents and electric fields to compute the electric field at the source  $\mathbf{E}_2$ , from which the corrected RCS can be extracted.

The two formulations, though complementary, are not equivalent, and cannot be expected to give the same results in general. In [1], only the M/H case was considered. The M/H formulation does seem to have an important advantage over the J/E formulation: physical optics and physical equivalence are often used to solve for electric currents on the shadowing body, and the integrals relating these electric currents to magnetic near fields are simpler in form to those relating the same electric currents to electric near fields. We will examine both formulations and compare the results with full-wave EM simulation results in Section 4.

### 3. Experimental Validation

To provide a simple case which can be used to validate the methodology presented here, we consider the case of two PEC spheres which are placed a small distance from one another. This represents a useful canonical case, since the scattered near fields from a PEC sphere are known exactly [2]. The geometry of the test case is shown in Fig. 2.

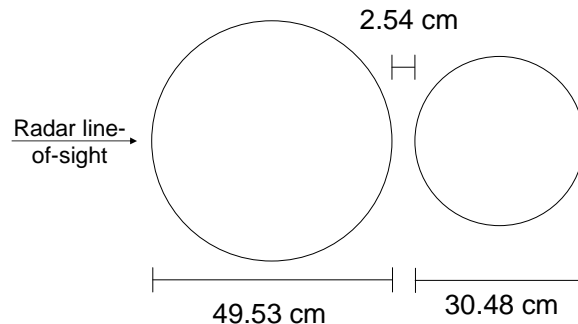


Fig. 2: Geometry of two spheres test case at 0 degrees aspect angle. The smaller sphere is shadowed by the larger.

The target complex was surveyed at X-band from 9-11 GHz, and the intensity of the primary scatterer of the smaller sphere was investigated as it moved out of the shadow of the larger sphere. To extract the RCS from measurement data, wideband images with a 5 deg integration window were used. Four such images are shown in Fig. 3 for different aspect angles. Due to diffraction of electromagnetic energy around the larger sphere, the smaller sphere is slightly visible at 0 deg aspect. At 20 deg, the smaller sphere is almost completely obscured. At 40 and 60 deg aspect, this scatterer can be seen to slowly move out of the shadow region.

The M/H formulation of the present shadowing technique was then applied to predict the degree of shadowing as a function of aspect angle. The center frequency, 10 GHz, was used in the computation of the shadowing adjustments. The intensity of the shadowed scatterer is shown as a function of aspect for VV and HH polarizations in Fig. 4. The results indicate that the observed gradual emergence of the smaller sphere from the shadow of the larger is predicted by the present shadowing theory.

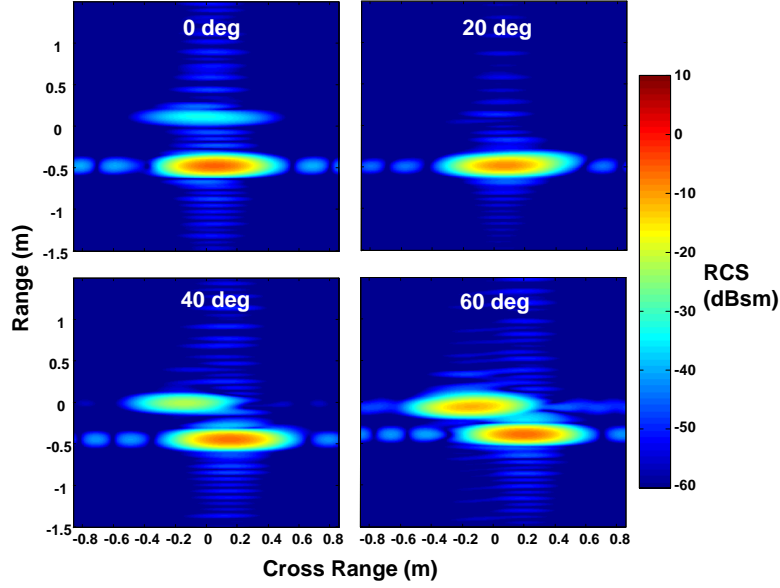


Fig. 3: Wideband images from measurement of two spheres target complex. The smaller sphere is mostly shadowed directly above the scatterer from the larger sphere at 0 deg aspect. This scatterer gradually grows in intensity at higher aspects as it moves out of the shadow.

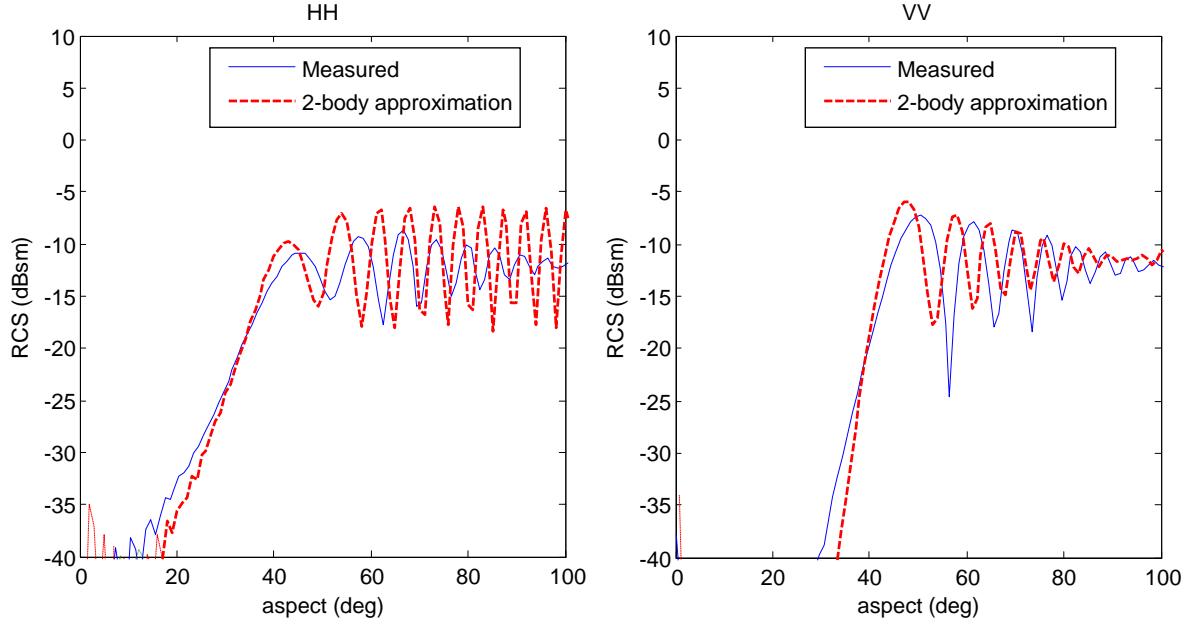


Fig. 4: Comparison of shadowing predictions for the two spheres validation case for VV and HH polarization.

#### 4. Planar PEC Shadowing Objects

We next consider the case where the shadowing body is a planar surface at  $z = 0$ , since physical optics can be used to readily obtain an approximation of the near fields. We shall consider both the M/H and J/E formulations.

### A. M/H Formulation

For the M/H formulation, the TM fields can be expressed by integrating over the planar region in the  $x - y$  plane:

$$\begin{aligned} H_{ys, TM} &= \frac{-z\Phi}{2\pi\eta} \int_S dx' dy' e^{-j\beta x' \sin \theta_i} e^{-j\beta r} \left( \frac{j\beta}{r^2} + \frac{1}{r^3} \right), \\ H_{zs, TM} &= \frac{\Phi}{2\pi\eta} \int_S dx' dy' (y - y') e^{-j\beta x' \sin \theta_i} e^{-j\beta r} \left( \frac{j\beta}{r^2} + \frac{1}{r^3} \right). \end{aligned} \quad (5)$$

The fields for the TE case are

$$\begin{aligned} H_{xs, TE} &= \frac{\Phi}{2\pi\eta} \cos \theta_i z \int_S dx' dy' e^{-j\beta x' \sin \theta_i} e^{-j\beta r} \left( \frac{j\beta}{r^2} + \frac{1}{r^3} \right), \\ H_{zs, TE} &= \frac{\Phi}{2\pi\eta} \cos \theta_i \int_S dx' dy' (x - x') e^{-j\beta x' \sin \theta_i} e^{-j\beta r} \left( \frac{j\beta}{r^2} + \frac{1}{r^3} \right). \end{aligned} \quad (6)$$

We assume all other Cartesian components than those defined above are zero.  $\Phi$  is 1 for  $0 < \theta_i < \frac{\pi}{2}$  and -1 for  $\frac{\pi}{2} < \theta_i < \pi$ , while  $r = \sqrt{(x - x')^2 + (y - y')^2 + z^2}$ . Then, the scattering corrections for the M/H formulation can be computed from the total fields (incident plus scattered) using

$$\begin{pmatrix} g_{yy} & g_{y\xi} \\ g_{\xi y} & g_{\xi\xi} \end{pmatrix} = \begin{pmatrix} -H_{y, TM} & -H_{\xi, TM} \\ H_{y, TE} & H_{\xi, TE} \end{pmatrix}, \quad (7)$$

where the minus signs are simply due to the assumed direction of the incident fields for the TE and TM cases.

### B. J/E Formulation

We can also consider the J/E formulation, which proceeds along similar lines. The TM fields are

$$\begin{aligned} E_{xs, TE} &= \frac{-j\omega\mu\Phi}{2\pi\eta\beta^2} \int_S dx' dy' e^{-j\beta x' \sin \theta_i} e^{-j\beta r} \left( \frac{\beta^2}{r} + (x - x')^2 \left( \frac{-\beta^2}{r^3} + \frac{3j\beta}{r^4} + \frac{3}{r^5} \right) - \frac{j\beta}{r^2} - \frac{1}{r^3} \right), \\ E_{ys, TE} &= \frac{-j\omega\mu\Phi}{2\pi\eta\beta^2} \int_S dx' dy' (x - x')(y - y') e^{-j\beta x' \sin \theta_i} e^{-j\beta r} \left( \frac{-\beta^2}{r^3} + \frac{3j\beta}{r^4} + \frac{3}{r^5} \right), \\ E_{zs, TE} &= \frac{-j\omega\mu\Phi z}{2\pi\eta\beta^2} \int_S dx' dy' (x - x') e^{-j\beta x' \sin \theta_i} e^{-j\beta r} \left( \frac{-\beta^2}{r^3} + \frac{3j\beta}{r^4} + \frac{3}{r^5} \right), \end{aligned} \quad (8)$$

while the TE fields are

$$\begin{aligned} E_{xs, TE} &= \frac{-j\omega\mu\Phi}{2\pi\eta\beta^2} \cos \theta_i \int_S dx' dy' (x - x')(y - y') e^{-j\beta x' \sin \theta_i} e^{-j\beta r} \left( \frac{-\beta^2}{r^3} + \frac{3j\beta}{r^4} + \frac{3}{r^5} \right), \\ E_{ys, TE} &= \frac{-j\omega\mu\Phi}{2\pi\eta\beta^2} \cos \theta_i \int_S dx' dy' e^{-j\beta x' \sin \theta_i} e^{-j\beta r} \left( \frac{\beta^2}{r} + (y - y')^2 \left( \frac{-\beta^2}{r^3} + \frac{3j\beta}{r^4} + \frac{3}{r^5} \right) - \frac{j\beta}{r^2} - \frac{1}{r^3} \right), \\ E_{zs, TE} &= \frac{-j\omega\mu\Phi z}{2\pi\eta\beta^2} \cos \theta_i \int_S dx' dy' (y - y') e^{-j\beta x' \sin \theta_i} e^{-j\beta r} \left( \frac{-\beta^2}{r^3} + \frac{3j\beta}{r^4} + \frac{3}{r^5} \right). \end{aligned} \quad (9)$$

The scattering corrections for the J/E formulation can be computed using

$$\begin{pmatrix} g_{yy} & g_{y\xi} \\ g_{\xi y} & g_{\xi\xi} \end{pmatrix} = \begin{pmatrix} E_{\xi, TM} & E_{y, TM} \\ E_{\xi, TE} & E_{y, TE} \end{pmatrix}. \quad (10)$$

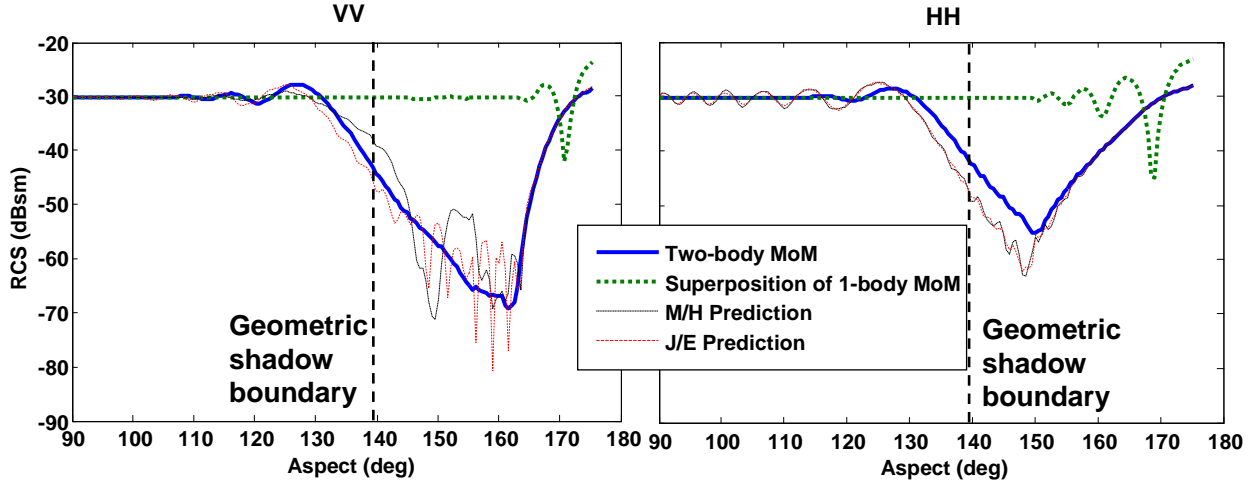


Fig. 5: Shadowing prediction for disc-sphere geometry.

To compare the techniques, we consider the plate to be a circular disc of 35 cm radius. A 2 cm radius sphere is placed 37.5 cm away from the disc along the center axis, and arranged such that the sphere is completely behind the disc at 180 degrees. The target complex was simulated at X-band from 9-11 GHz using CICERO MoM code [3]. Three CICERO simulations were carried out, two single body simulations with the disc and the sphere, and one with the two-body target complex. The extracted RCS at the expected scatterer location is shown in Fig. 5. Clearly, a superposition of one-body returns does not produce a representative signature. The present technique produces a signature that is much closer to the full two-body MoM simulation even though a very crude physical optics approximation was used for the currents. The signature fluctuation at 180 deg is due to range sidelobe interference from the disc scatterer.

For the HH polarization case, the M/H and J/E prediction methods yield nearly identical results. However, the predictions yielded different results in the VV case. Judging from the present results, the J/E formulation may yield slightly better predictions, but somewhat more computational effort is required.

## 5. Conclusion

A technique has been presented to evaluate two-body electromagnetic interactions for cases where the shadowing object (facing the radar) is a canonical object whose near fields can be computed. The technique has been validated using static range measurements and a MoM-based prediction code. Two different shadowing formulations were evaluated and compared. These methods could provide a useful tool for adjusting scattering center models when objects are closely spaced.

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